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origin and evolution of a glaciated shelf

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HAMILTON BANK, LABRADOR MARGIN

Origin and Evolution of a Glaciated Shelf

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ABSTRACT

Hamilton Bank consists of a thick wedge of Mesozoic and Cenozoic sediments that was built out over a block-faulted, subsiding Precambrian crystalline basement. Subsidence was in response to the same forces that caused the opening of the Labrador Sea and the separation of Greenland and North America. The gross final relief was formed through alternating phases of valley erosion and of deposition corresponding to periods of glacio-eustatic lowered and raised sea level.

The bank was first glaciated during the Illinoian, and a thick layer of drift was deposited. Advances and retreats of the Wisconsinan ice sheet on Hamilton Bank are recorded by the distribution of subaqueous glacial and proglacial landforms. Kames and kettles and meltwater channels developed beneath a grounded stagnant ice sheet. Outwash plain deposits occur directly seaward of the meltwater channels. End moraines identify stages of ice movement. The distribution of ground moraine and kames and kettles on Hamilton Bank identifies phases of rapid and slow deglaciation. Deglaciation is estimated to have occurred between 10 000 and 8 000 years ago.

Postglacial sediment dynamics has been largely a matter of winnowing and local redeposition of glacial deposits. The bulk of the fine clays that accumulated in the deepest parts of the marginal trough in early postglacial time seems to have been derived from the inner shelf while the Labrador Current was confined to the outer edge of the shelf. In the past 6 000 years or so, however, the Labrador Current adopted a course closer to shore, through Cartwright Saddle and the marginal trough.

Icebergs calved from the Greenland Icecap are carried southward across Hamilton Bank by the Labrador Current. Where they touch bottom furrows are gouged up to several meters deep and several kilometers long.

RÉSUMÉ

La structure du Banc Hamilton est caractérisée par une formation sédimentaire épaisse en biseau, mésozoïque et cénozoïque, déposée sur un soubassement cristallin précambrien affaissé et fortement faillé. L'affaissement de la marge continentale est dû aux contraintes qui ont formé la mer du Labrador et séparé le Groenland et l'Amérique du Nord. Le relief final s'est sculpté durant des périodes alternatives d'érosion fluviatile et de dépôt correspondants aux oscillations glacio-eustatiques du niveau de la mer.

La glaciation du Banc a commencé durant l'Illinoisien, lorsque les dépôts glaciaires épais se sont accumulés. La morphologie sous-marine glaciaire et proglaciaire atteste des avances et des retraits des calottes glaciaires du Wisconsin sur le Banc Hamilton. Des « kames and kettles » et des cours d'eau de fonte se développent sous une calotte glaciaire stagnante. Des dépôts d'eau de fonte se situent a leur embouchures. Les moraines frontales indiquent les phases du mouvement des lobes de glace. La distribution des moraines de fond, des « kames and kettles » sur le Banc Hamilton permet d'identifier des périodes de déglaciation rapides ou lentes. Nous estimons que la déglaciation s'est effectuée entre 10 000 et 8 000 ans B.P.

Au cours de l'Holocène les dépôts glaciaires ont été remaniés et redéposés, tandis que les argiles, accumulées dans les parties les plus profondes du chenal marginal, sont provenues,

elles, du plateau continental intérieur. Au début de cette époque, le courant du Labrador s'est limité à la marge extérieure du plateau continental. Cependant, depuis 6 000 ans, il s'écoule plus près de la côte, par le Cartwright Saddle et le chenal marginal.

Des icebergs issus de la calotte glaciaire du Groenland sont emportés vers le sud par le courant du Labrador et passent sur le Banc Hamilton. Lorsque les « quilles » des icebergs touchent le fond, elles le labourent en formant des sillons qui peuvent atteindre quelques mètres de profondeur et plusieurs kilomètres de longeur.

INTRODUCTION

In the past decade a number of geological and geophysical reconnaissance surveys (Grant 1972) were conducted in the Labrador Sea (Fig. 1; Map 831 A), examining the structure, stratigraphy, and evolution of this northwestern arm of the Atlantic Ocean and of the adjacent Canadian continental margin. Appreciable thicknesses of sediment were found to underlie the Labrador shelf. As a consequence, the region has attracted exploration activity in a search for structures suggesting accumulations of oil and gas.

The surface of the outer Labrador shelf is covered by a veneer of glacial drift, over 100 m thick in places. Since deglaciation this material has been altered by bottom currents and the gouging of icebergs. The area thus provides an excellent opportunity to study the influences of glacial, periglacial, and postglacial conditions on a continental shelf. At the same time, economic and environmental interests require an appreciation of the difficulties of mineral exploration in the area. In response to these stimuli, the Atlantic Geoscience Centre, Bedford Institute of Oceanography, began a pilot study of the shelf, focusing on Hamilton Bank (Map 831 A) because that region offered the best hydrographic and geophysical control on the Labrador margin.

FIG. 1. Bathymetric map of the Labrador Sea region showing major physiographic features. Area A depicts the outline of Fig. 2, 3, 9, and 11. Area B is that covered by maps 831 A, G, and M (in pocket).

This paper reports on the results of bottom sediment sampling and geophysical and hydrographic profiling on Hamilton Bank during the summers of 1972 and 1973. Incorporated are the findings of previous studies dealing more specifically with the dynamics of surface sediments and their distribution (Stewart 1974; van der Linden 1974; Fillon 1976) as well as the distribution of relict glacial sediments and associated subaqueous landforms (Fillon 1975). W. J. van der Linden was responsible for the collection of data, for the textural analysis of sediments, and interpreted the structural history and the effects of iceberg furrowing; R. H. Fillon compiled maps 831 M and G and interpreted the geomorphological, glacial, and postglacial history; D. Monahan compiled map 831 A and supervised map production.

METHODS

BATHYMETRY

The bathymetric map of Hamilton Bank (Map 831 A, in pocket) was constructed from three sets of data. In 1972 CSS *Hudson* obtained bathymetric profiles along a series of east–west tracks approximately 18 km apart, as well as along a few crosslines. The ship was continuously positioned by Loran C, which was checked against satellite fixes. Positioning errors are estimated not to exceed ± 120 m of latitude and ± 220 m of longitude. Depths were measured using the Bedford Institute of Oceanography's Gifft-Alpine echo sounding system.

In 1973 CSS *Dawson* obtained additional bathymetric information from Hamilton Bank, running lines with a variable spacing between 5 and 10 km. Navigation and sounding methods were identical to those of the 1972 CSS *Hudson* survey.

Also in 1973, Eastcan Exploration Ltd. provided soundings that had been collected during exploration activities in previous years. These data were produced by many different methods and the density and orientation of tracks varies considerably. The original records are not available. Depths were reported as numerical values plotted on charts.

Data from all sources were examined and values at track crossovers compared. The data are largely consistent from source to source and only a few tracks disagree sufficiently to warrant adjustment or rejection. The numerical data were contoured by hand. This interpretation has been checked against the analogue profiles and revised where necessary.

Seismic Reflection

During the 1973 survey aboard CSS *Dawson* two independent seismic reflection programs were run simultaneously, one using a surface-towed low frequency system, the other a deep-towed high frequency system. The surface-towed system fired either a 5- or 10-inch airgun as sound source that produced a usable frequency range from about 60 to 700 Hz, peaking at 150 Hz. The deep-towed system (Nova Scotia Research Foundation 1973) employed a 165-J sparker with frequencies ranging from about 3 to 5.5 kHz, depending on depth of operation. The airgun system permitted penetration of up to 700 m of sediment with a maximum resolution of about 20 m. The sparker unit provided a penetration of up to 40 m of sediment and could resolve vertical differences of about 1 m. In the horizontal sense, however, the resolution was only about 10 m at the 50 cm/h paper speed of the recorder. The areal coverage of the two systems is indicated in Fig. 2.

Side-Scan Sonar

A side-looking sonar, developed by the Bedford Institute of Oceanography (Jollymore 1974), was used during the 1973 survey (Fig. 2). The system scanned the sea bottom at right angles to the ship's track with an acoustic signal in the 70 kHz range. Display of echoes on a two-channel Mufax split-helix recorder gave a hyperbolically distorted

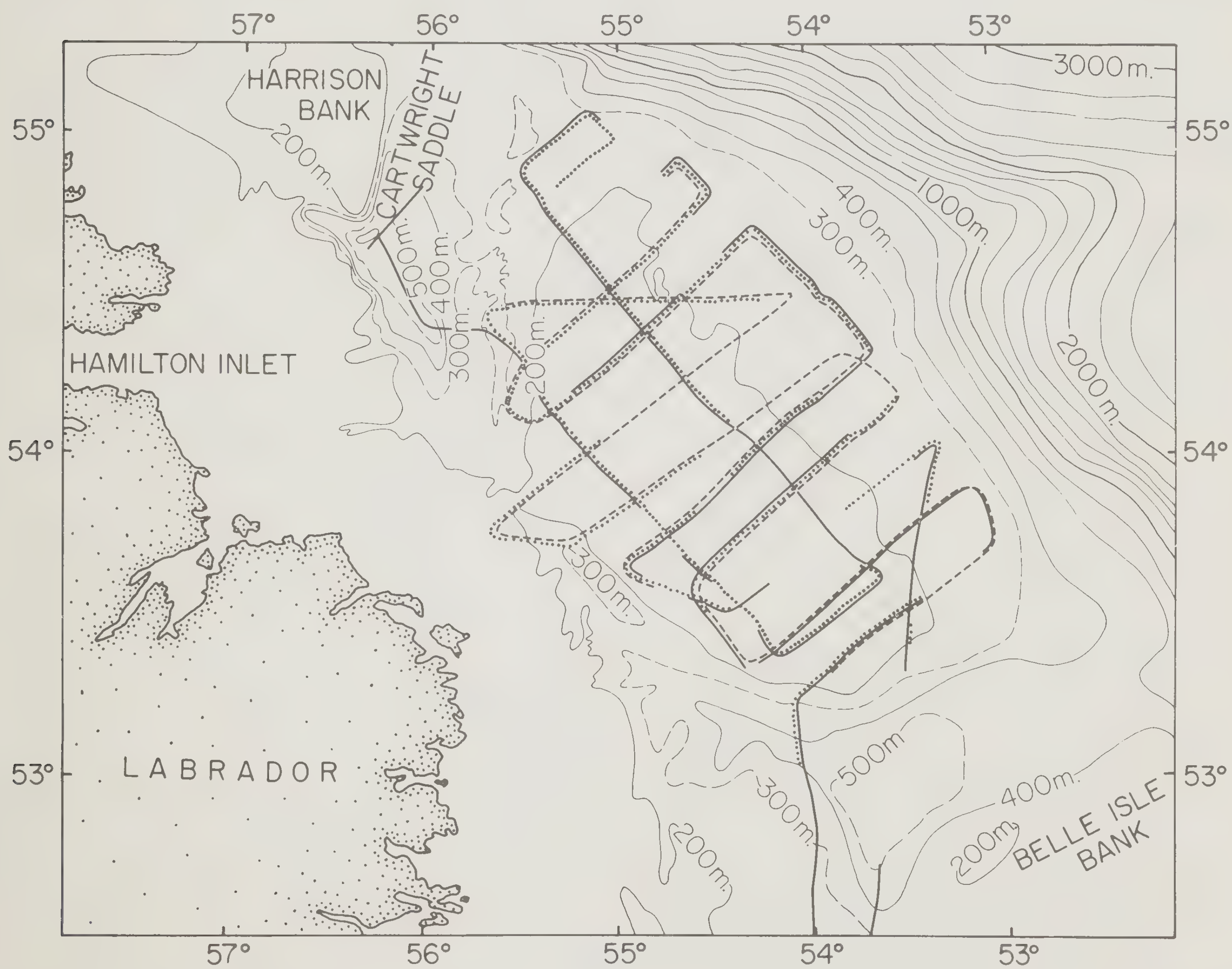


FIG. 2. Trackline chart of Hamilton Bank, CSS *Dawson* cruise 73-027. Solid lines indicate coverage by airgun reflection seismics; dotted lines, deep-towed sparker reflection seismics; and dashed lines, side-scan sonar.

view of the sea bottom. At shelf depths of about 200 m the record shows two strips of sea bottom 400–500 m wide on both sides of the ship, separated by a "blind" area about 600 m wide directly beneath the vessel.

Bottom Sampling, Granulometry, and Underwater Photography

During cruises of CSS *Dawson* in 1973 and CFAV *Sackville* in 1972 and 1973, bottom sediment samples were collected using a van Veen grab with a jaw opening of 35 cm. Samples showing evidence of alteration during recovery (e.g. when a pebble prevented the jaws from closing tightly) were not considered in this investigation. Sample locations are shown in Fig. 3.

The samples were stored in sealed plastic buckets and returned to the Bedford Institute of Oceanography for grain-size analysis. Sieving and pipetting procedures allowed determination of weight percents for fractions from -5ϕ to 10ϕ at 1ϕ intervals for 28 samples. Weight percents for the -5ϕ to 4ϕ fractions as well as total silt (4ϕ to 8ϕ) and total clay (finer than 8ϕ) were determined for 132 samples.

A total of 22 camera stations (Fig. 3) were occupied during the last phase of the CSS *Dawson* cruise. The sites were selected on the basis of side-scan sonar information and bottom samples. A number of bottom photographs from each camera station were used for identification of sedimentological and small scale morphological characteristics.

PREGLACIAL GEOLOGY

Structure

The deep structure of the Labrador continental margin has been deduced largely from seismic information (Fenwick et al. 1968; Mayhew et al. 1970; Grant 1972, 1975a; van der Linden and Srivastava 1975; van der Linden 1975). Stratigraphic information is scarce, and thus the timing of events

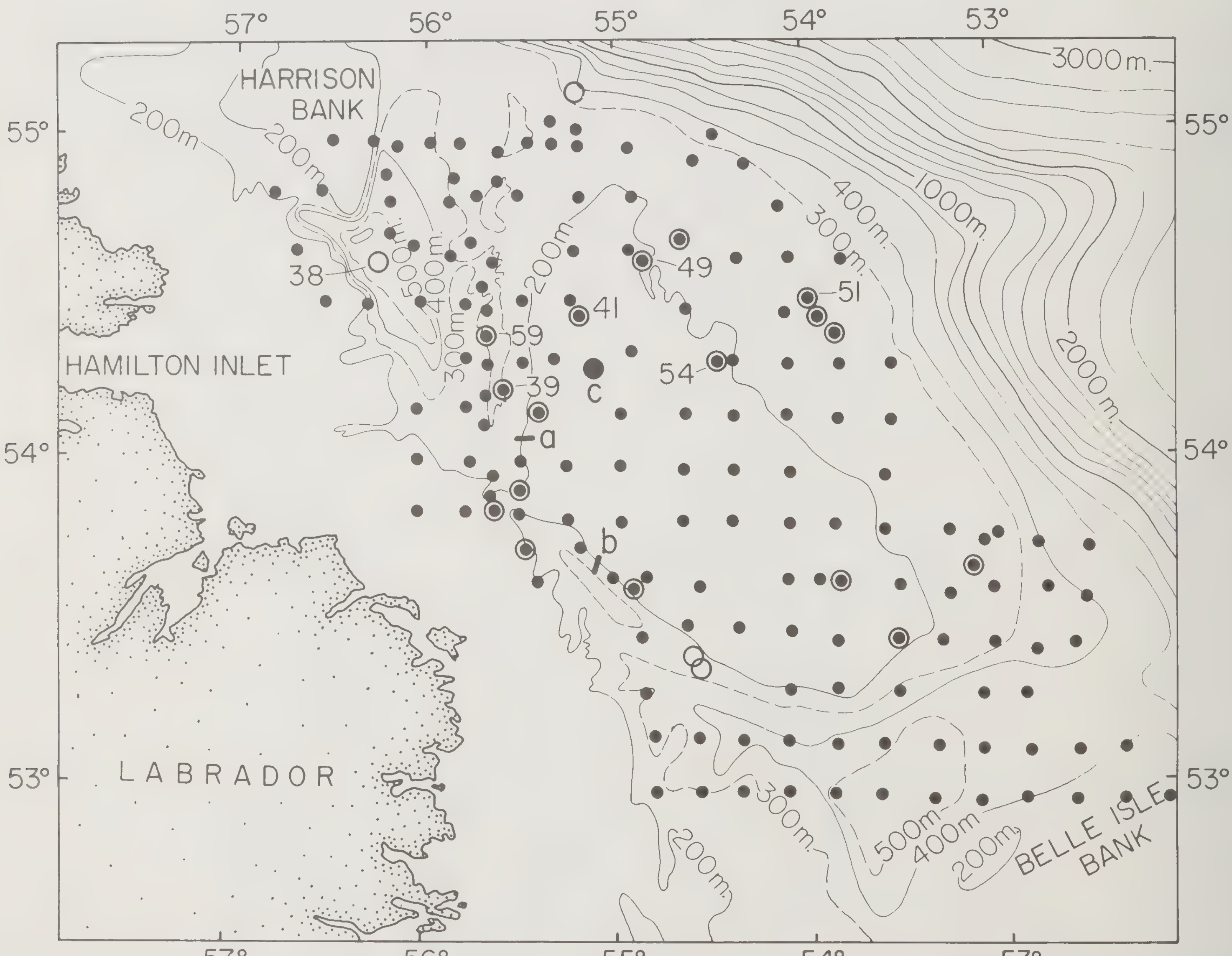


FIG. 3. Sample localities. Solid dots, sediment sample stations; open circles, camera stations. Photographs taken at numbered sites are reproduced in Plates 1, 2, and 3. Short cores were recovered from sites a and b (Slatt and Lew 1973) and c (Well site Tenneco Leif E-38).

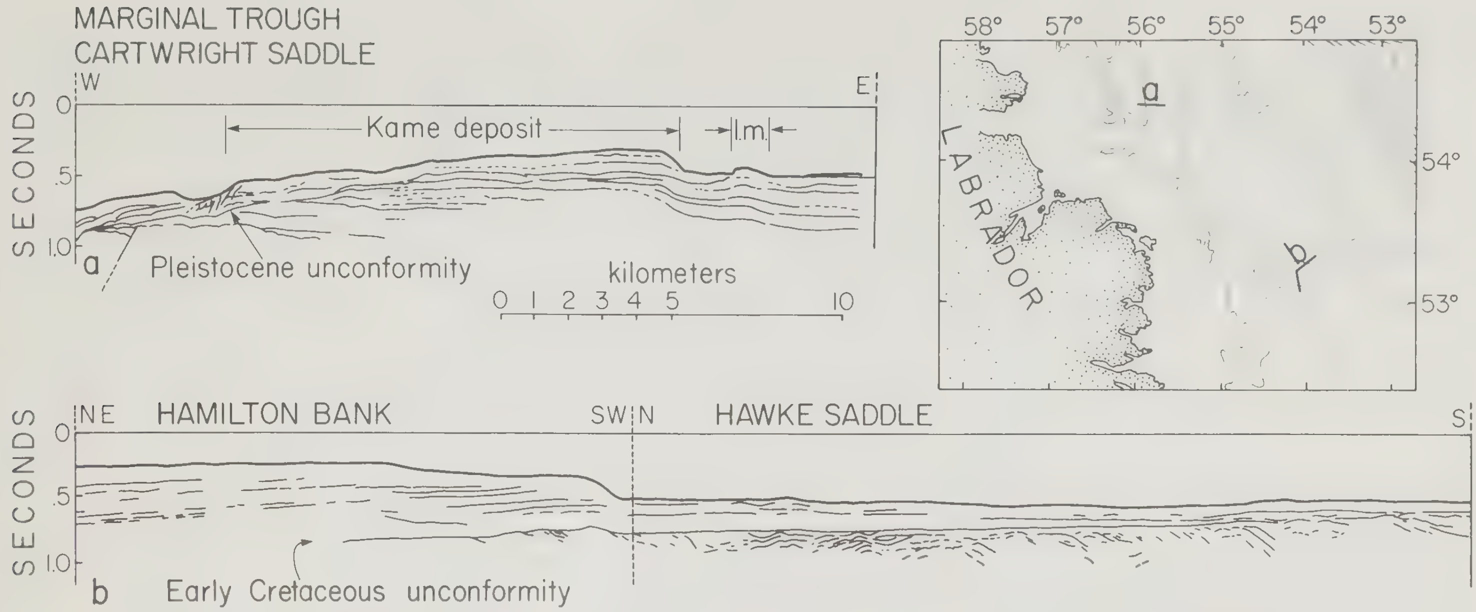


Fig. 4. Interpretation of airgun seismic profiles over (*a*) Cartwright and (*b*) Hawke saddles. Note extent of large kame deposit and occurrence of lateral moraine (l.m.).

and knowledge of environmental conditions during the evolution of the Labrador margin is still speculative. Seismic reflection records obtained during the CSS *Dawson* 1973 survey over Hamilton Bank and periphery supplement and confirm Grant's (1972) data. They reveal a structure generally characteristic of the Labrador margin from the Grand Banks to Davis Strait.

Hamilton Bank is underlain by gently seaward-dipping coastal plain strata that are covered unconformably by semistratified glacial drift (Fig. 4*a*). The coastal plain deposits in turn unconformably overlie folded sediments (Fig. 4*b*). The age of the latter unconformity and that of the sediments below are not known with certainty. Grant (1972) suggested that the folded beds might be Carboniferous sequences, extending north from Newfoundland. More recently, Grant (1975a) considered as an alternative a Jurassic age for the folded sediments and suggested that the overlying unconformity might be an extension of an Early Cretaceous unconformity which is observed on the Grand Banks. Because Jurassic sediments on the Grand Banks were deformed by the movement of underlying salt (Jansa and Wade 1975), it seems plausible that the same process was active beneath Hamilton Bank (van der Linden 1975).

Beneath the inner Labrador shelf, landward of Hamilton Bank, the folded sediments are missing, and undeformed coastal plan deposits directly overlie a rough basement, the offshore extension of the Precambrian Labrador Shield. In the nearshore region the basement is largely exposed in a rough rocky zone covered with thousands of islets and shoals.

Continental Margin Evolution

A generalized history of the Labrador margin (Fig. 5) is beginning to emerge from recent studies (van der Linden 1975). The region developed in response to the same processes that were responsible for the formation of the Labrador Sea Basin mainly in Mesozoic and Tertiary time. During the Paleozoic, the Precambrian continental lithosphere in the region of the future Labrador Sea was elevated, presumably by thermal expansion of the underlying asthenosphere. Basins developed marginal to the area of upwarp caused by an elastic downward bending of the lithosphere below its equilibrium position. Sediments collected in these marginal basins on a Precambrian basement, initially in epicontinental seas with restricted circulation, a condition favorable for the accumulation of evaporites. Sediment loading caused further subsidence of the crust and thus several kilometers of shallow marine deposits gradually accumulated. Seismic refraction and reflection data suggest that for the Labrador margin at least, the subsiding crust under the marginal basin thinned to <10 km, probably because of assimilation of the lower crust into the upper mantle, and that intensive fracturing and faulting took place. Fracturing and failure of the crust most likely was accompanied by widespread intrusion of basalts. Continental fragments (Flemish Cap, Orphan Knoll [Fig. 1], and other blocks in the north) separated from Labrador while, in between, subsidence of the widening marginal basins continued. Increased sediment loading mobilized the evaporites in the deep basins (halokinesis) with the result that the overlying sediments were folded by Late Jurassic time.

Nonmarine conditions in the Late Jurassic–Early Cretaceous (I. Hardy 1975 personal communication) indicate that an inversion of relief took place (Fig. 5*b*), perhaps because of the mushrooming and collapse of the thermally expanded asthenosphere that had initially elevated and stretched the central region. As a result, the central Labrador Basin opened, centered on an emerging ridge system, the Mid-Labrador Sea Ridge. At the same time the marginal basins were pushed up, a process that may have contributed to further folding of the Mesozoic sediments. This event heralded a period of erosion for the margin during which several hundred meters of folded Jurassic sediments were removed.

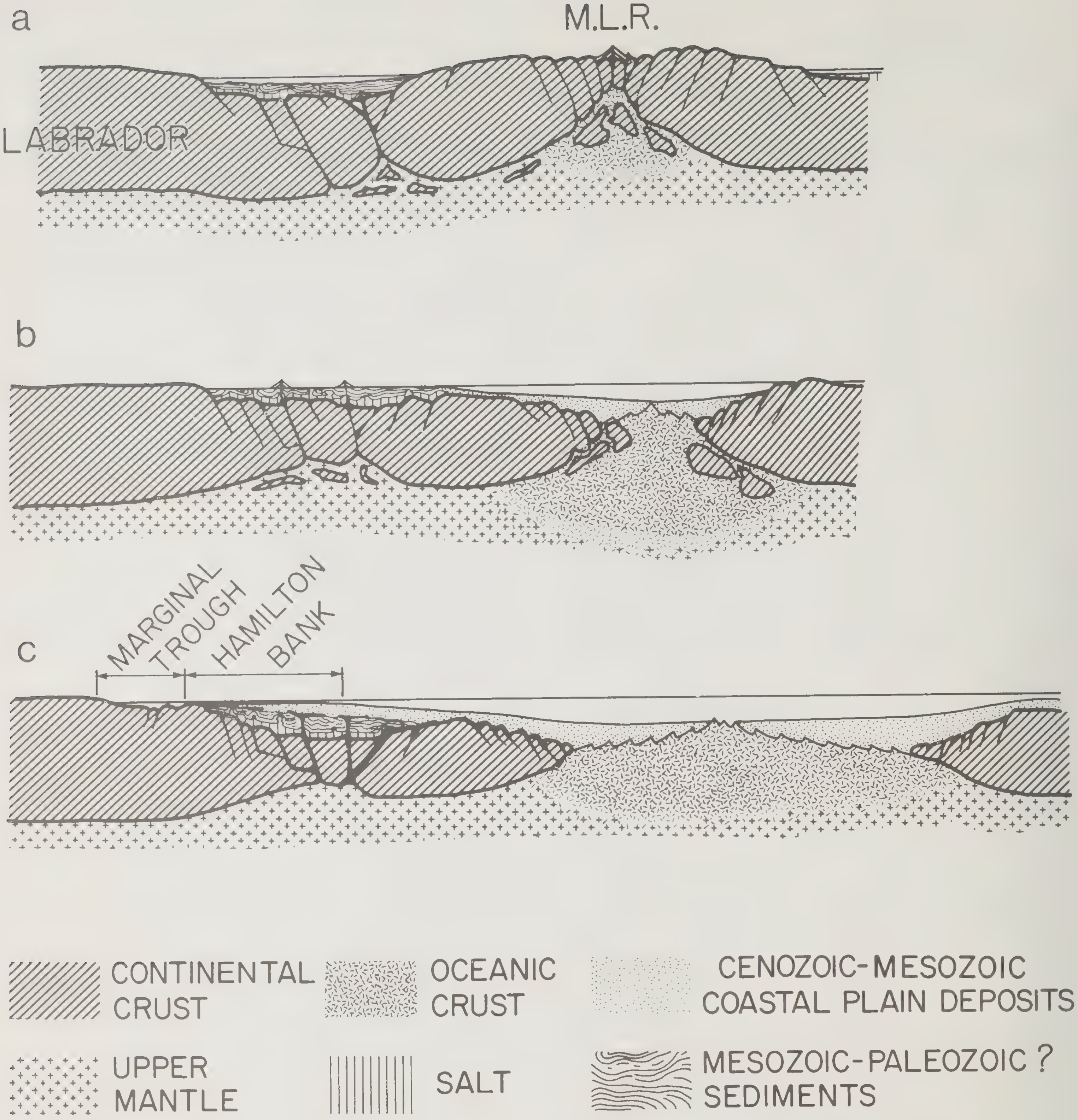


FIG. 5. Evolution of the Labrador margin as the result of crustal attenuation and seafloor spreading. M.L.R. is Mid-Labrador Sea Ridge; *a*, Paleozoic–Late Jurassic; *b*, Cretaceous; *c*, Tertiary–Quarternary.

Toward the Late Cretaceous, when the formation of the central Labrador Sea was largely completed, a new phase of deposition began, with the whole region subsiding to its final isostatic level. A renewed phase of seafloor spreading during the Tertiary in the North Atlantic and southern Labrador Sea does not seem to have had much effect on the sedimentation regime in the Labrador marginal basin. From seismic evidence, accumulation of coastal plain sediments appears to have been largely uninterrupted from the Late Cretaceous until the onset of Quaternary glaciation.

Landscape Evolution

The outer Labrador shelf consists of a number of isolated banks that are separated from the inner rocky shelf or "skjaergaard" (Holtedahl 1970) by the Labrador Marginal

Trough. Hamilton Bank is isolated from neighboring Harrison and Belle Isle banks by Cartwright and Hawke saddles respectively. These depressions trend obliquely across the shelf and coalesce with the marginal trough. A narrow sill with a threshold of 190 m interrupts the trough southeast of the junction with Cartwright Saddle.

The troughs on the Labrador shelf and similar troughs off other glaciated lands may have been cut by glaciers (Shepard 1931) or created by faulting and subsidence of portions of the crust (Holtedahl 1950). Recent seismic evidence (Grant 1972) reveals that portions of the Labrador Marginal Trough are bordered by faults. Faulting still seems to occur locally in the trough (Grant 1970). The absence of faults in many areas implies that other factors played a significant role in developing the present morphology.

The thickest accumulations of glacial drift on the Labrador shelf south of 58°N (Fig. 6) occur seaward of former outlets (Prest 1970) of continental ice tongues. The pattern of drift on the shelf between Baffin Island and 58°N suggests that it accumulated at the junction of coalescing ice lobes flowing out of Hudson and Davis straits. Drift on the Labrador shelf thus appears to have been largely derived from terrestrial sources and not from glacial excavation of the marginal trough–saddle system. A substantial amount of drift has accumulated in the trough and saddles (Fig. 6).

Evidence from a well drilled on Hamilton Bank (Leif E-38, Tenneco 1973) indicates that, during the Late Pliocene–Early Pleistocene, the ancestral Churchill River debouched 300–400 m of deltaic sands on the subsiding shelf. Glacioeustatic sea level fluctuations have occurred throughout most of the Pliocene and Pleistocene in response to the waxing and waning of northern hemisphere ice sheets (Berggren and Van Couvering 1974). Thus, before the shelf subsided to its post-Illinoian (500 000 yr ago) level, rivers such as the Churchill would have had ample opportunity to erode a system of marginal and transverse troughs at times of low sea level. The cross-sectional profile of Hawke Saddle (Fig. 4), which reveals a gross surface morphology similar to terrestrial river valleys (Palmquist 1975), supports this interpretation. Intermittent expansion of continental ice sheets onto the shelf during the past 500 000 yr (Fillon 1976) modified the valleys, perhaps by deepening portions and elsewhere by depositing glacial debris, giving them their present saddle-shaped profiles (Map 831 A).

Extensive alteration of drainage basins and river courses by ice movement on land, especially during glacial periods of the Pleistocene, produced numerous lakes and impoundments. Sediment eroded from the land is deposited in these inland basins which, during a short interglacial, are not completely filled. Thus, the amount of river detritus transported to the continental shelf during short interglacials, e.g. the Sangamon and Recent, was minimal. At an average depth of 190 m, Hamilton Bank is anomalously deep compared to shelves in nonglaciated regions. Continental margin subsidence has apparently outstripped the sedimentation rate. The net result has been a gradual structural deepening of the shelf and, in places, probably more rapid deepening of the troughs. Subsidence of 90 m in 500 000 yr at a rate of 18 cm/1000 yr

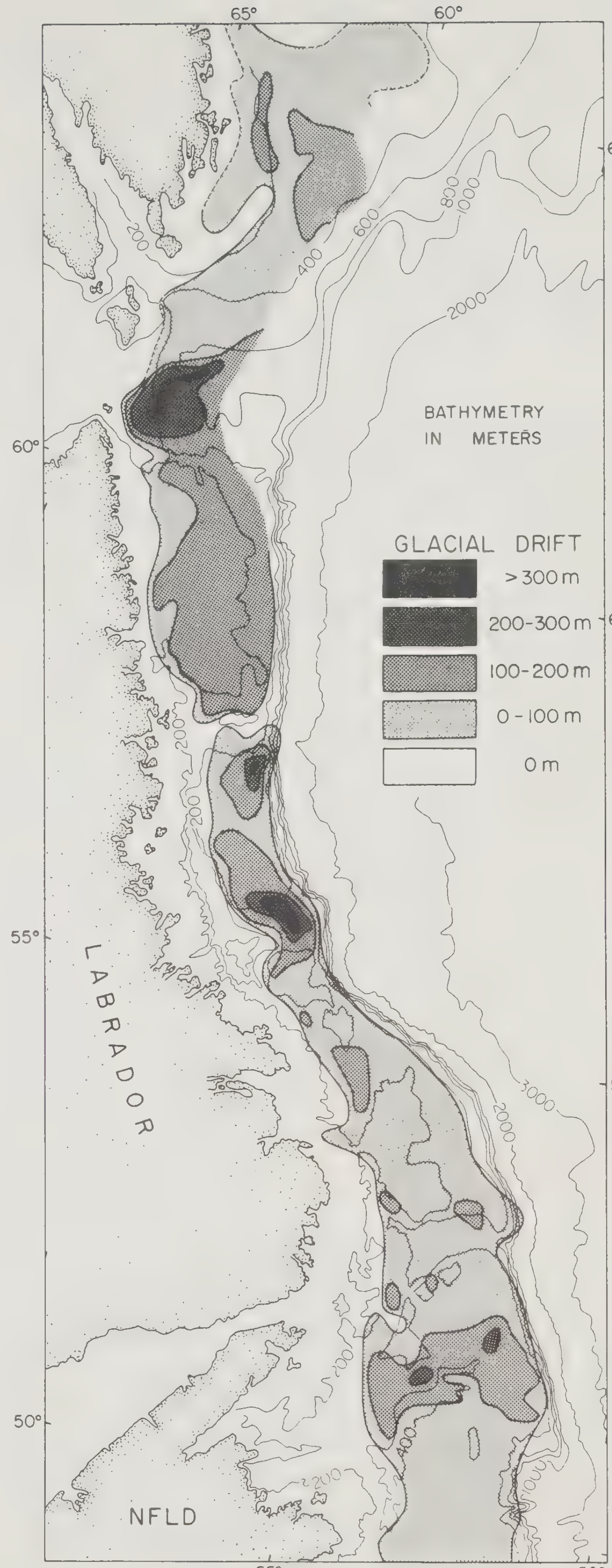


FIG. 6. Thickness of glacial drift along the western Labrador Sea margin from airgun reflection seismics after Grant (1972, 1975b).

is implied. This is close to the average apparent sedimentation rate for the Miocene in Leif E-38 of 19 cm/1000 yr (Tenneco 1973).

In summary, the above considerations imply that the troughs and saddles, although to some extent controlled by faults and modified by glacial processes, were largely cut by river erosion. Marginal and transverse channels are probably not unique to glaciated shelves. During glacial low stands of sea level, similar drainage patterns were cut on shelves in other parts of the world; however, high postglacial sedimentation rates in nonglaciated areas have subsequently filled and masked the underlying erosional relief.

GLACIAL GEOLOGY

Background

In comparison to the glacial geology of the present land area of Canada (Prest 1970), the glacial geology of the continental shelves is still poorly understood. The continental shelves are important to our understanding of the history of glaciation in Canada because the glaciers terminated on the shelves in the north and east. That is where evidence of fluctuations of the old ice sheet margins and the beginnings of the end of the last ice age will be found recorded in the sediments. Tentative evaluation (Fillon 1976) of Leif E-38 borehole data indicates that glaciation on Hamilton Bank began during the Illinoian about 500 000 yr ago.

King and co-workers were the first to undertake a detailed surficial geology study of a portion of the Canadian Shelf. Their findings (King 1967, 1969, 1970; King et al. 1972) may be taken as proof that the Laurentide Ice Sheet extended onto the shelf off Nova Scotia. Banks on the Scotian Shelf were found to have been subaerially exposed after deglaciation. Hamilton Bank, on the other hand, was not emergent during or after the disintegration of the Laurentide Ice Sheet in the Wisconsinan (Fillon 1976). Wisconsin glacial features on Hamilton Bank are therefore much better preserved than those on the Scotian Shelf banks, which were eroded in a migrating beach-zone.

Glacial Landforms

Map 831 M, Relict Subaqueous Glacial Landforms, reflects the excellent state of preservation of glacial features. It summarizes information compiled from bathymetric profiles, deep-towed V-fin sparker profiles, and side-scan sonar records. To produce this map, on which most of the interpretation of Hamilton Bank glacial geology has been based, morphological bottom types were classified according to the wavelength and amplitude of small- and large-scale surface undulations measured on echo-sounding and V-fin records. The size and apparent intensity of mottles (irregularly shaped, patchy, sometimes spotty markings of variable size) observed on side-scan sonar records provided complementary information.

In this way, the Hamilton Bank region was divided into five zones of different degrees of bottom roughness. Each bottom roughness class (Fig. 7 *a–d*) has been interpreted as a specific subaqueous glacial or proglacial landform and is comparable with analogous features already known onshore.

Moraines, large kames, and subglacial meltwater channels have also been recognized (Fig. 7*e*, 4*a*, and 7*f* respectively). Moraines, the most obvious relict landforms on Hamilton Bank, are topographically rough, appearing almost jagged, and are identical in transverse section to those described on the Scotian Shelf by King (1969) and King et al. (1972). Curvilinear moraine trends can be traced across the bank and along the marginal channels (Map 831 M). These are not terminal moraines, because glacial features occur to seaward indicating that Wisconsinan ice extended for a time to the shelf edge where it probably flowed into a fringing ice shelf (Fillon 1975).

Portions of Hamilton Bank are characterized by extremely irregular topography (bottom roughness type I, Fig. 7*a* and Map 831 M) with a macrorelief of 15–30 m and a half wavelength of 4–8 km. Superimposed on these undulations is a microrelief of 1–10 m with a half wavelength of 50–800 m. Distinct mottles appear frequently on side-scan sonograms from these areas.

Bottom roughness type I is morphologically similar to kame and kettle topography, like that described on land near Lake Melville by Wenner (1947), for example. The sediments cored in this area (Slatt and Lew 1973) also closely resemble those of kame and kettle deposits (Fillon 1975). Therefore the features on Hamilton Bank are referred to as subaqueous kames and kettles.

Subaqueous kames and kettles were probably formed beneath a stagnant, grounded ice sheet (Fig. 8). Irregular melting produced water-filled crevasses and sub-ice cavities in which glacial debris accumulated to form piles of stratified drift. Where supporting masses of ice remained grounded, subaqueous kettle holes developed in among subaqueous kame deposits. The existence of cavities beneath the ice sheet on Hamilton Bank is supported by the presence of sub-ice meltwater channels that wind across the bank. One large channel shows up plainly on map 831 A (54°06′N 54°40′W to 54°25′N 54°50′W).

Directly seaward of the relict meltwater channel mouths is a large area that appears flat on deep-towed sparker profiles (bottom roughness type II, Fig. 7*b*). The overall relief shows amplitudes < 2 m and half wavelengths of about 10–500 m. Mottling on side-scan sonograms of bottom type II occurs only in areas where this type grades into bottom type I. On the basis of morphology and position, this region is interpreted as an analogue of a terrestrial outwash plain. Sand-size and finer material was carried from beneath the stranded ice sheet through the meltwater channels and spread seaward over the ice-free shelf (hyperpycnal flow) (Fig. 8). The effect of the Labrador Current may be responsible for the increasing width of the submarine outwash plain in a southerly direction away from the major sub-ice channel (Map 831 M).

Bottom roughness type III — macrorelief < 5 m, half wavelength about 4 km, and microrelief 1–5 m, half wavelength 20–100 m — is interpreted as subaqueous ground moraine (Fig. 7*c*), formed under moving ice. The moraine was not destroyed by subsequent stagnation of the ice

that elsewhere led to the formation of subaqueous kames and kettles. Mottling is only occasionally apparent on the sonograms in areas of bottom type III.

Intermediate between subaqueous ground moraine and subaqueous kame and kettle topography is bottom roughness type IV (Fig. 7*d*)—macrorelief 10–30 m, half wavelength about 2 km, and microrelief 2–5 m, half wavelength 20–400 m without mottles. It may have formed beneath the ice sheet at a stage of reduced flow and partial stagnation.

Areas of smooth bottom (bottom roughness type V, not shown) are confined to basins in Cartwright and Hawke saddles and the marginal trough. They are similar morphologically to bottom type II, but are known from sparker profiles to be acoustically transparent. Piston cores (Vilks et al. 1974) show the deposit to be composed of silts and clays. These strata were deposited in postglacial times and are more fully discussed in the next section.

Deglaciation

The sequential positions of the ice sheet margin during deglaciation as inferred from the distribution of bottom roughness types and moraines are shown in Fig. 9. Patches of ground moraine preserved near the seaward edge of the bank (Map 831 M) imply that initial retreat of the ice from a position at the shelf edge (Stage 1, Fig. 9*a*) must have occurred rapidly by calving with little chance for stagnation and formation of kame and kettle deposits. Once the easternmost edge of what is now the subaqueous kame and kettle band (Stage 2, Fig. 9*a*) was reached, deglaciation proceeded more slowly, resulting in the obliteration of ground moraine and the formation of subaqueous kames and kettles. The ice front must have gradually retreated to an indeterminate position (Stage 3, not illustrated) landward of the prominent end moraine complex on the bank (Map 831 M). The moraine complex could only have been produced during a subsequent ice readvance (Stage 4, Fig. 9*b*). The path of readvance is marked by the large area of ground moraine landward of the end moraine. Lying along the landward edge of the bank is a linear strip of subaqueous kame and kettle topography. It is inferred that when the ice front finally retreated from the end moraine position, it did so again rapidly. Only along the landward edge of the bank in the marginal trough (Stage 5, Fig. 9*b*) did remnants of the ice sheet remain sufficiently long for subaqueous kames and kettles to develop.

In the transverse channels a complex distribution of end moraines, lateral moraines, kames and kettles, and ground moraine occurs. Ice in the channels was substantially thicker than on the bank and was sustained much longer by discharge from coastal glaciers. Fluctuations of the ice front here were much more restricted than on the bank. Figures 9*c* and *d* show generalized ice marginal positions during this phase of deglaciation.

Deglaciation of the Hamilton Inlet portion of the Labrador coast has not been dated conclusively. Estimates range from 16 000 to 14 000 years ago (Prest 1970) to 10 000 to 8 000 years ago (Wenner 1947). The latter correlates well with local ^{14}C dates (Hodgson and Fulton 1972) and with the recorded warming of ocean water in the eastern Arctic (Andrews 1972), which would have warmed the ice sheet, decoupling it from the substratum and triggering rapid deglaciation.

POSTGLACIAL SEDIMENTS

Introduction

Surficial sediment types (gravels, sands and muds) found on Hamilton Bank are common on glaciated continental shelves throughout the world (Shepard 1963). Shepard (1932) and Emery (1952, 1968) argue that these sediments are relict. Others (Swift et al. 1971) contend that they were extensively reworked and redistributed under conditions similar to those of today and are thus largely in equilibrium with the present environment. These conflicting points of view emphasize the fine line of distinction between preserved ancient sediments and the reworked products of those sediments.

Hamilton Bank was not subaerially exposed during late Wisconsinan or post-Wisconsinan time (Fillon 1976). Because it is isolated from the inner shelf, it provides a unique opportunity to study the effect of superimposing marine outer continental shelf environmental conditions on continental ice sheet deposits.

Grain-size analyses were made of 160 grab samples, representative of about the upper 25 cm of sediment. This information has been compiled and is presented on Map 831 G, Surficial Geology. Generalized textural types (gravel, sand, mud) and informal sedimentary map units are shown. The latter separate surficial sediments into types that can be distinguished without detailed analysis. These are further subdivided according to modal sediment type, a more precise system discussed in detail elsewhere (Fillon 1976).

Sediment Distribution

Around the perimeter of Hamilton Bank is a band of sediment (map unit 1) which ranges from dominantly sand (subunit 1a) to dominantly gravel (subunit 1b). This deposit, informally termed the Cartwright sand and gravel, is widest along the eastern edge of the bank. Landward the amount of pebble and coarser material decreases with a corresponding increase in sand. Bottom photographs (Plate 1 *a–f*, p. 18–23) show a patchy veneer of sand overlying a coarser surface.

The gravels comprising subunit 1b are angular, implying a glacial till origin. We suggest that the Cartwright sand and gravel developed as a lag deposit in response to the erosion and removal of the finer sediment sizes from Wisconsin kames and ground moraine. This appears to have been accomplished by relatively high velocity bottom currents associated with storm waves (Fillon 1976).

The Groswater unit (map unit 2) is an informal name applied to the deposit of muddy fine sand to fine sandy mud that covers the interior surface of Hamilton Bank. As shown on sparker profiles, it is typically < 1 m thick although in depressions it may reach 10 m thick. Cores

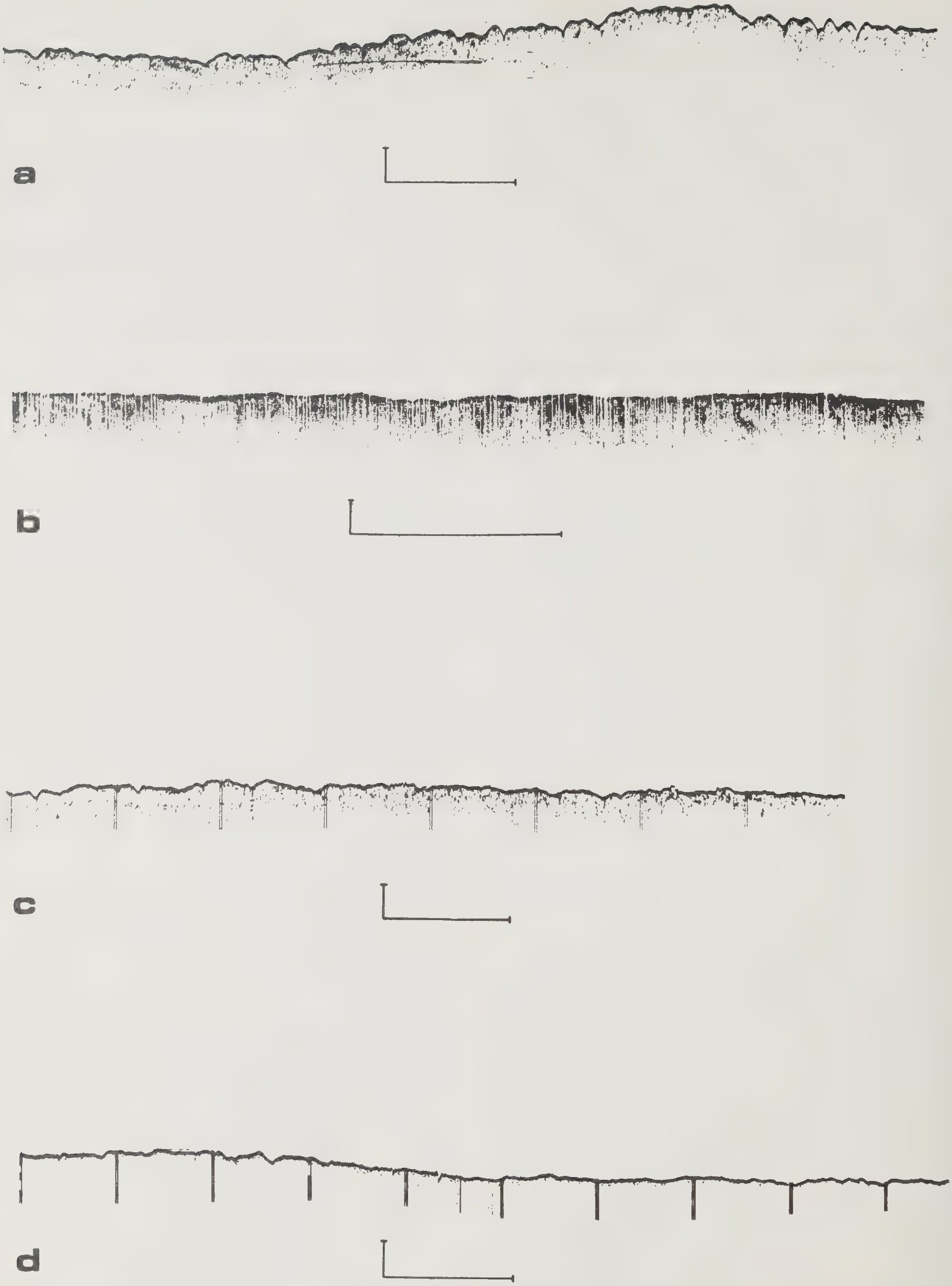
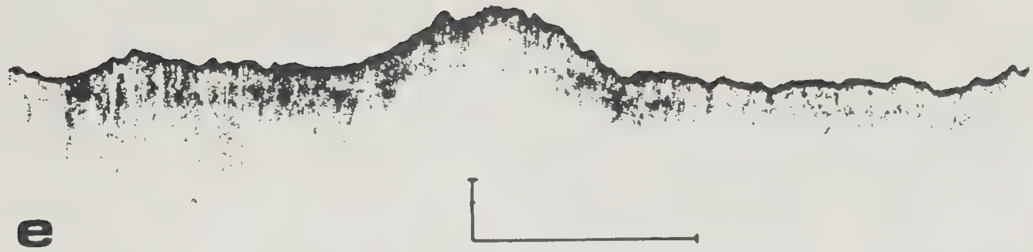
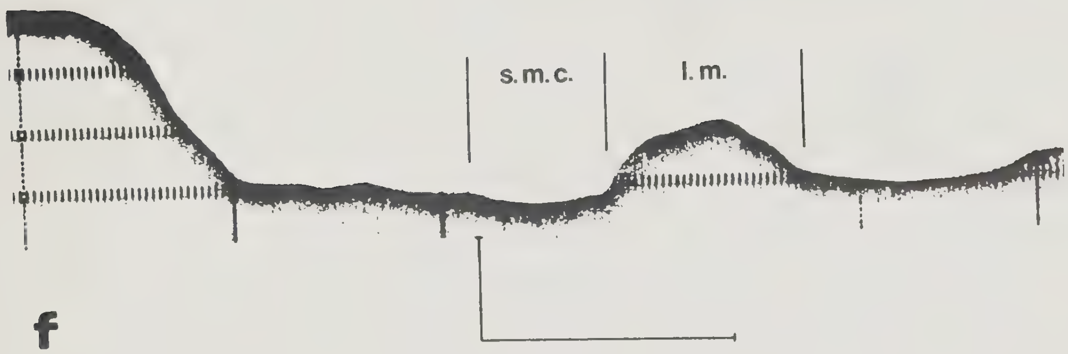


FIG. 7. *a–d*, representative deep-towed sparker profiles of bottom roughness classes I through IV. Section *e* is a sparker profile over an end moraine. Section *f* is a precision echo sounder record over a subglacial meltwater



e



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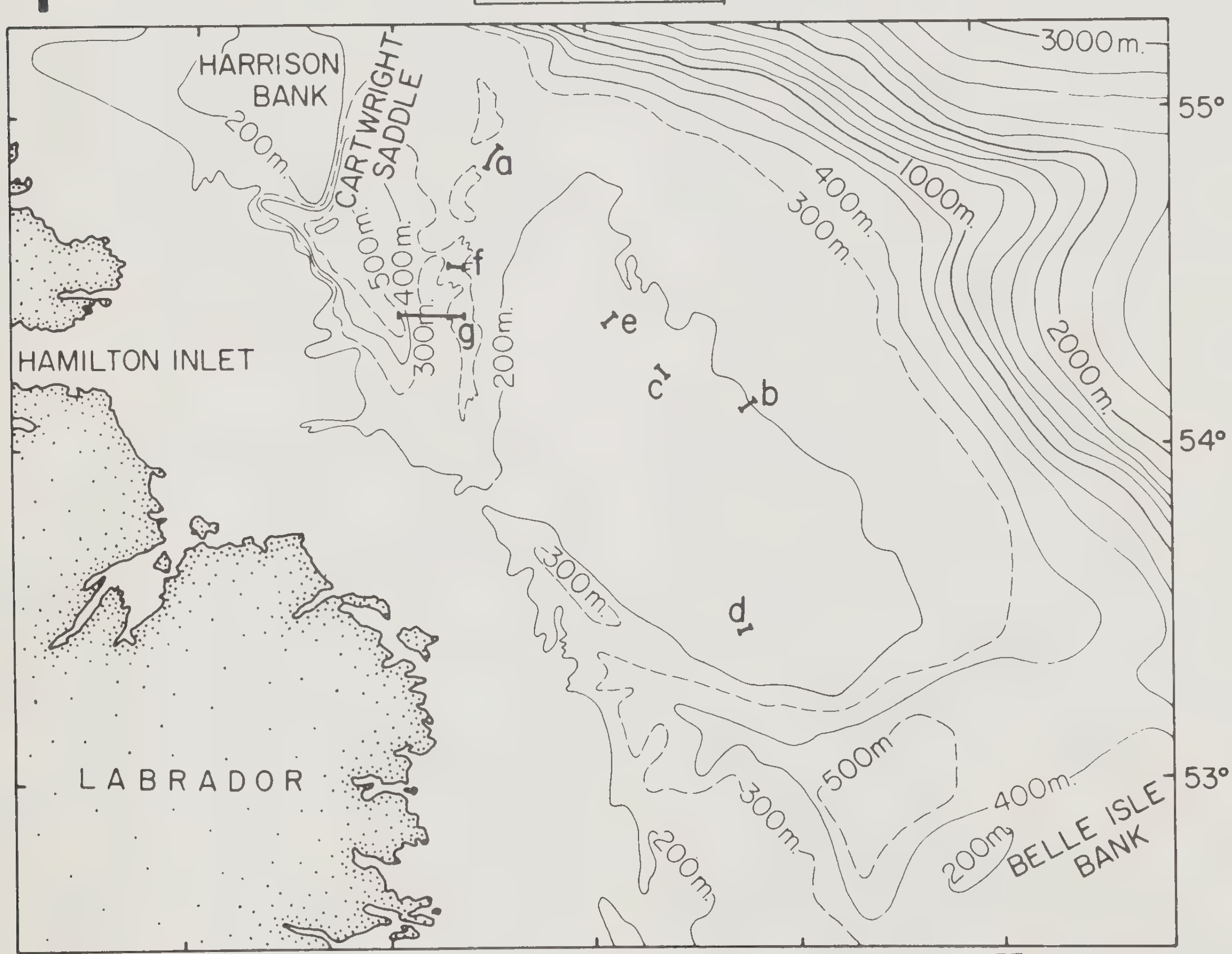


channel (s.m.c.) and a lateral moraine (l.m.). Vertical scale bars represent 10 m (*a–e*) and 50 m (*f*). The horizontal bar is in all cases equivalent to 1000 m.

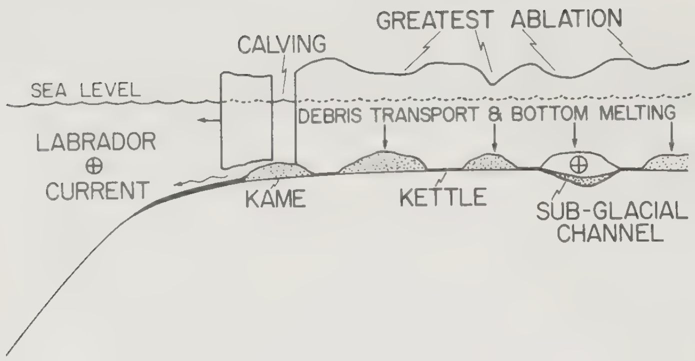


FIG. 8. Schematic representation of stagnant ice sheet (Fillon 1975). Semi-stratified drift, stippled; outwash sediments, black.

described by Slatt and Lew (1973) reveal that in places it is underlain by semi-stratified material that probably comprises Wisconsin subaqueous kames (Fillon 1975).

The source of the Groswater sediment is apparently the fine fraction that was removed during the formation of the Cartwright sand and gravel. Bottom photographs (Plate 2 *a–f*, p. 24–29) show a depositional surface with many animal burrows and little indication of scour by currents. The Groswater unit is predominantly sand, but grades into mud in the southwestern portion of the area. This is due to the greater distance over which finer particles were transported by the southerly flowing Labrador Current (Dunbar 1951).

In the preceding section it is mentioned that basins in the troughs adjoining Hamilton Bank are filled with very fine-grained sediments. These are mostly silty clays. A minor sand size component consists largely of plant and animal remains. As in the case of the Groswater unit, bottom photographs (Plate 3 *a–b*, p. 30–31) reveal a depositional surface with indications of biogenic activity but no current scour. We have applied the informal name Goose clay to this deposit (map unit 3).

The Goose clay is thick, up to 20–50 m in the deepest parts of the basins (Vilks et al. 1974). Analysis of the volumes of various grain sizes within the Cartwright sand and gravel and the Groswater unit, in comparison with the composition of underlying glacial drift, leads us to believe (Fillon 1976) that a significant portion of the Goose clay must have been derived from sources other than the erosion of Hamilton Bank.

The surface sediments in Cartwright Saddle contain Foraminifera and diatoms that live in waters over the outer continental shelf. The Labrador Current appears to have carried the remains of these organisms, along with silt and clay particles, into Cartwright Saddle and the marginal trough. The route followed by the Labrador Current along the Labrador shelf implies that at present most of the Goose clay is derived from the northern banks. This has not always been the case. Prior to about 6 000 years ago the Labrador Current in the vicinity of Hamilton Bank was confined to the outer edge of the shelf (Fillon 1976). This is confirmed by Vilks et al. (1974), who show that the foraminiferal fauna preserved 3 m below the bottom is dominated by *Elphidium clavatum*, indicative of inshore and estuarine conditions in the arctic and subarctic. Thus at the time of deposition the net transport of water was from the inner shelf to Cartwright Saddle.

Along the upper continental slope several widely spaced samples indicate the occurrence of very fine sands and silts. These deposits are probably extensive and may eventually constitute an additional map unit. Seaward of the Cartwright sand and gravel, the coarser portions of these slope sediments are very similar to those of the Groswater unit and may have been formed in a similar fashion, i.e., by the accumulation of material winnowed from the eroded bank edge.

ICEBERG GOUGING

ICEBERGS IN THE LABRADOR SEA

The effects of ice on the physiography of the Labrador margin did not end with the retreat and disappearance of the Laurentide Ice Sheet from the shelf. As testified by side-scan sonograms (Fig. 10), Hamilton Bank is gouged or ploughed by the keels of icebergs that are carried southward over the bank by the prevailing currents. These icebergs are calved mainly from the Greenland Icecap where it reaches the sea, notably in Melville Bight and Disko Bight, West Greenland. It has been estimated that about 20 000 bergs are calved into Baffin Bay (U.S. Naval Oceanographic Office 1973). Initially most of them are carried north by the prevailing West Greenland Current. In northern Baffin Bay many bergs, not caught in coastal inlets, are swept westward and then southward, first by the Canadian Current and subsequently by the Labrador Current. More than 2 500 bergs pass Cape Chidley, the northern tip of Labrador (McMillan 1973) and about 400 reach the Grand Banks every year (U.S. Naval Oceanographic Office 1973). The size of the bergs varies considerably but some, weighing tens of millions of tons, have been observed grounded in water depths of several hundred meters.

GOUGE CHARACTERISTICS

Typically, ice furrows on Hamilton Bank are tens of meters wide but a few may reach maximum widths of about 200 m. The furrows are generally not more than 4 m deep. They are flanked by shoulders that are pushed up a few meters above the seafloor. Exceptionally deep furrows show overall relief of more than 10 m (Harris 1974). The maximum length of individual furrows, as observed from sonograms parallel to them, is at least several kilometers. Additional statistics on ice gouges were given by Harris and Jollymore (1974) for the Labrador shelf just south of Hamilton Bank.

The quality of images of ice scours on side-scan sonograms varies with water depth. Because of depth limitations of the sensor (length of the towing cable and pressure on transducers) the 1973 side-scan survey did not resolve bottom images below 250 m. Echo sounding records of ice gouges also lose resolution and become more difficult to interpret as water depth increases. Scours in deeper water, on the other hand, since they are made by bigger bergs, should be larger and thus easier to discern. However, in water depths greater than 200 m echogram resolution is such that it would be virtually impossible to

FIG. 9. Successive positions of grounded and floating ice during deglaciation. (Stage 3 is indeterminate and not shown.) Solid line (broken where uncertain) marks seaward edge of grounded active ice. Heavy dashed lines represent seaward edge of grounded stagnant ice remaining after retreat from active ice position by extensive calving. Inferred floating ice shelves are marked with hachures.

distinguish ice furrows superimposed on very rough glacial topography. Hence, conclusions on maximum depth of ice gouging based on such evidence are tenuous.

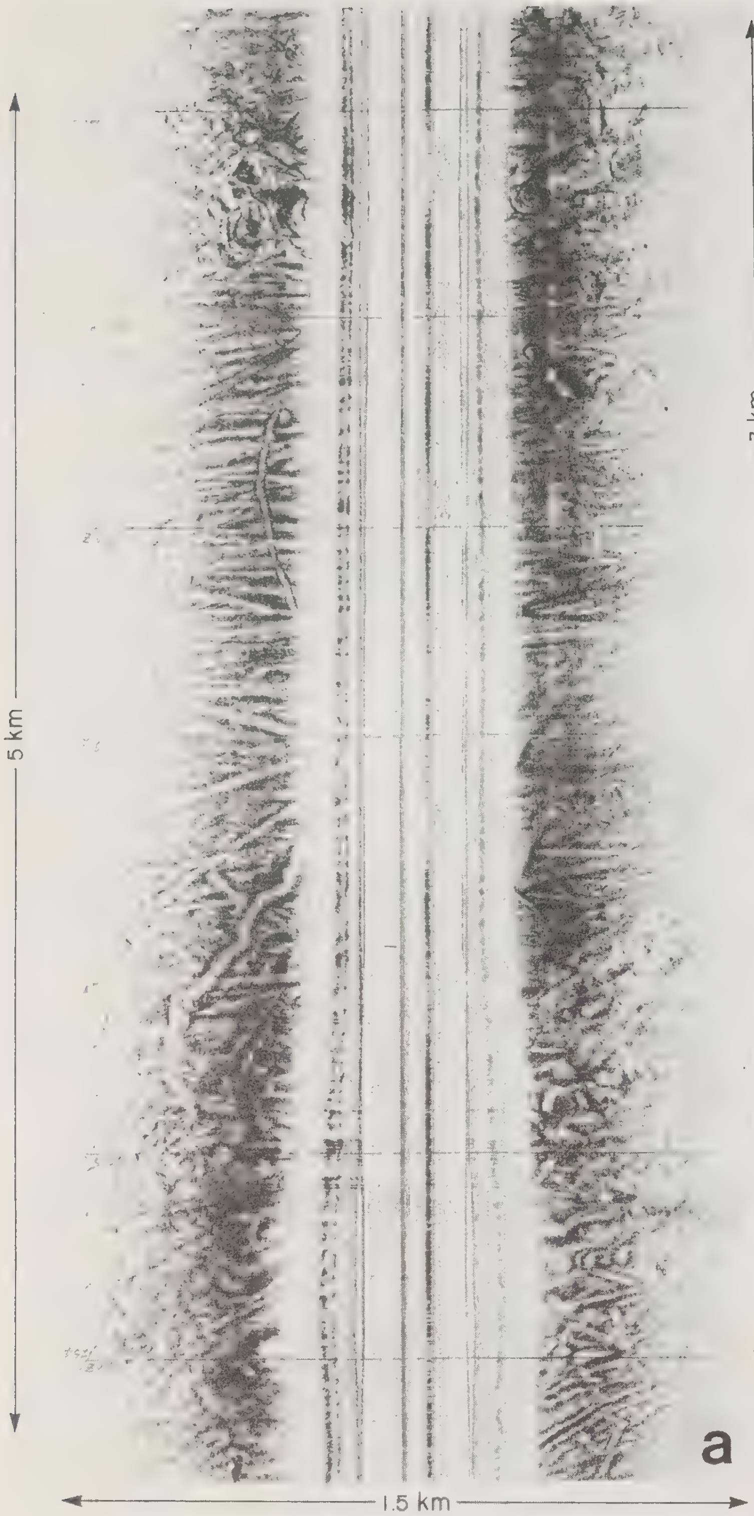
On Hamilton Bank some scours have a fresh appearance whereas others have subdued relief and appear to be eroded or masked by sediment cover. The reflectivity of the seabed as recorded by side-looking sonar depends on the bottom roughness, partially a function of grain size. The higher reflectivity of the furrow shoulders indicates increased roughness caused by the plowing process.

Draft of Icebergs

Future exploitation of the natural resources of the Labrador margin requires that the maximum water depths at which icebergs ground be known. These depths vary from area to area and correspond to the maximum draft of bergs passing over. Probably only observations of stranded bergs or direct measurements of keel depths will provide an unambiguous answer to this question. Maximum draft to height ratios of 5:1 for blocky bergs (Chari and Allen 1973) and the measured maximum height of Labrador Sea icebergs suggest that their keel depths would seldom exceed 400 m. Damage to underwater equipment in water depths of about 425 m has been reported for northern Baffin Bay (Milne 1969).

Orientation of Ice Gouges

Some gouges are fairly linear, others meander and testify to erratic berg movements. The sill between Cartwright and Hawke saddles displays linear scouring, oriented predominantly northwest–southeast (Fig. 10*a*). Mostly the patterns are more chaotic (Fig. 10*b*) although dominant orientations are recognizable. In other areas the scouring has produced a mottled pattern and generations of multidirectional furrows are superimposed (Fig. 10*c*).



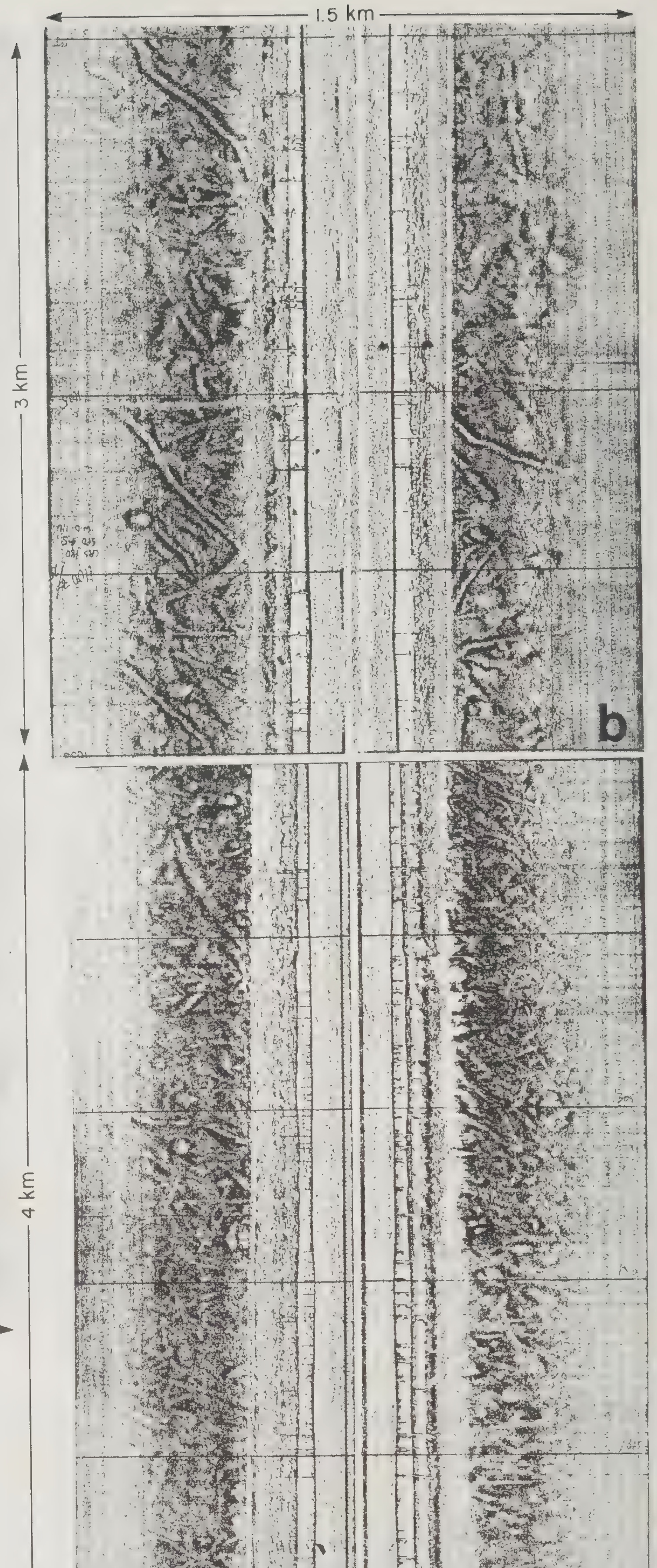


FIG. 10. Side-scan sonograms of ice gouges. *a*, predominantly northwest–southeast oriented scours across the sill between Cartwright and Hawke saddles. Note erratic motions of bergs as evidenced by scours between 1825 and 1830 h. *b*, chaotic pattern of ice gouges near Hawke Saddle. The dominant gouge trends are northeast–southwest. *c*, ice gouging pattern near the bank edge. No predominant orientation of berg movement is apparent.

To establish the general path of bottom-scouring ice over Hamilton Bank, ice gouges identified from the 1973 side-scanning sonograms for which azimuths could be measured have been mapped (Fig. 11*a*). Nomograms were used to correct for scale distortions of the sonograms so as to arrive at the true orientation of the scours relative to the ship's track. At distances of about 5 km along the track, i.e. at half-hour intervals, the scours were grouped into half vectors showing the dominant and first subdominant azimuth of scours for that interval. Averaging the scour directions was done by visual examination only. Interpolation of directions between tracks reveals a picture (Fig. 11*b*) that shows, not unexpectedly, a direct relation with gross morphological features and depicts the pattern of the Labrador Current as it flows over the bank. The pattern confirms that the motion of icebergs is largely controlled by the prevailing currents. The scatter of scour directions is explained by tidal and weather patterns, especially storms that are known to cause erratic movements of bergs (J. Allen 1975 personal communication).

Superimposed on the map (Fig. 11*a*) is the relative abundance of ice scours. This pattern again correlates with the morphology. Areas in the lee of shallows are relatively well protected from gouging. This observation is important in that it indicates areas where the problems of erecting structures on the seabed, such as production platforms and pipelines, are less complicated by dangers resulting from iceberg disturbance of the seafloor.

Age of Ice Gouges

Iceberg furrows ploughed during the Pleistocene have been preserved in shelf areas of western Europe (Belderson et al. 1973; Belderson and Wilson 1973). They are indistinguishable from many ice scours observed on the Labrador shelf. King (in press) observed ice gouges in the Laurentian Channel that looked fresh, yet he interpreted them as having been cut in Wisconsinan time. Because of lowered sea level at that time, Wisconsinan gouges should occur in water depths about 100 m deeper than those cut recently, if we assume that berg size has not changed in time. The Wisconsinan ice sheet was most likely grounded on the southern Labrador shelf until about 9 000 years ago, and thus the gouges are presumably not older than that. The gouges largely reflect the present route of the Labrador Current; because the route followed by the current was significantly different prior to about 6 000 years ago (Fillon 1976), the majority of measured gouges must have formed since then.

SUMMARY AND CONCLUSIONS

1) Semi-stratified glacial drift on Hamilton Bank rests unconformably on gently seaward dipping coastal plain strata which in turn unconformably overlie folded sediments of presumed Jurassic age. The folding may have been in response to salt migration as on the Grand Banks.

2) The folded sediments are interpreted to have been deposited within a subsiding basin marginal to a zone of uplift centered along the axis of the present Labrador Sea. Early Cretaceous shallowing of the marginal basin during the initial opening phase of the Labrador Sea permitted the development of an erosional surface. Renewed deposition began in the Late Cretaceous as isostatic subsidence of the entire Labrador Sea region brought the margin area below base level.

3) The Labrador Marginal Trough and channel system appears to have developed largely through fluvial erosion during periods of Pleistocene low sea level. Low postglacial sedimentation rates caused by glacial disruption of inland drainage failed to obscure the Pleistocene relief.

4) Wisconsinan glacial landforms dominate the mesoscale morphology of the bank. Features include end moraines, kames, subglacial meltwater channels, subaqueous kame and kettle fields, subaqueous outwash plain, and ground moraine. Wisconsinan ice retreated in stages from a maximum at the shelf edge. Initial retreat was probably in response to a climatic warming about 9 000 years ago, transforming the ice sheet from cold-based to wet-based. This resulted in a rapid decoupling from the substratum and catastrophic deglaciation.

5) Postglacial sediments on Hamilton Bank have been derived from glacial deposits. Stormwave erosion, concentrated at the bank edge, has produced sand and gravel lags. The winnowed fine sand and mud fractions are transported by the Labrador Current to the interior bank surface. At present the Labrador Current also sweeps suspended mud into Cartwright Saddle where it accumulates. However, benthic Foraminifera indicate that the thick sequences of muds deposited prior to about 6 000 yr ago had an inner shelf source.

6) The surface of Hamilton Bank has been gouged extensively by icebergs. Gouges range to 4 m deep and may extend for several kilometers. Groove orientations depict flow pattern of the Labrador Current across the banks as maintained for the past 6 000 yr. The density of gouges is locally dependent on topography, with the lowest concentrations in the lee of shallows.

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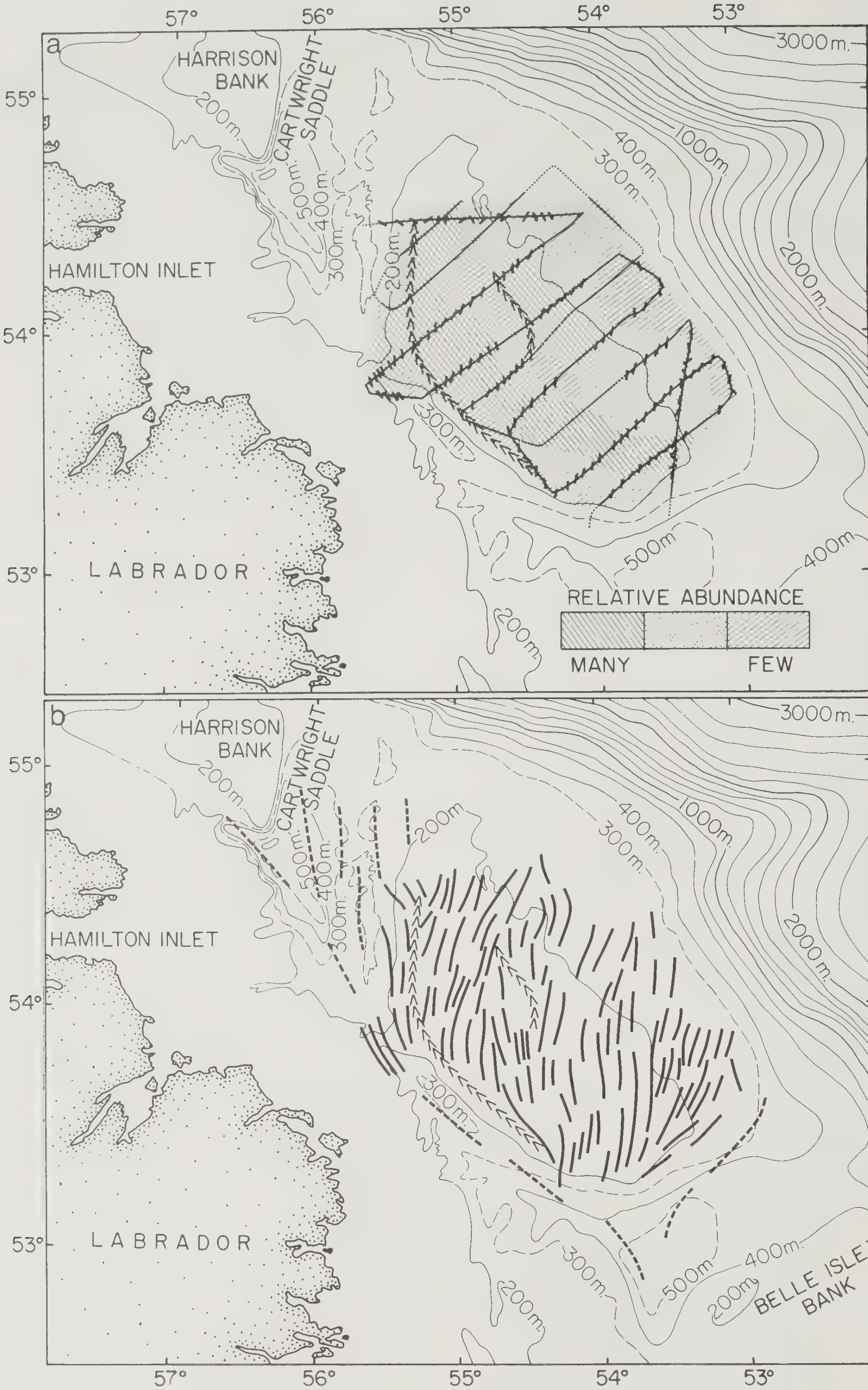

FIG. 11. *a*, dominant directions of ice gouging measured along ship's track. Superimposed is the relative abundance of furrows. The chains of Λ's indicate the trend of topographic ridges. *b*, direction of iceberg movement over Hamilton Bank. Solid lines deduced from direction of gouges (11*a*). Broken lines are inferred dominant flow lines of the Labrador Current.

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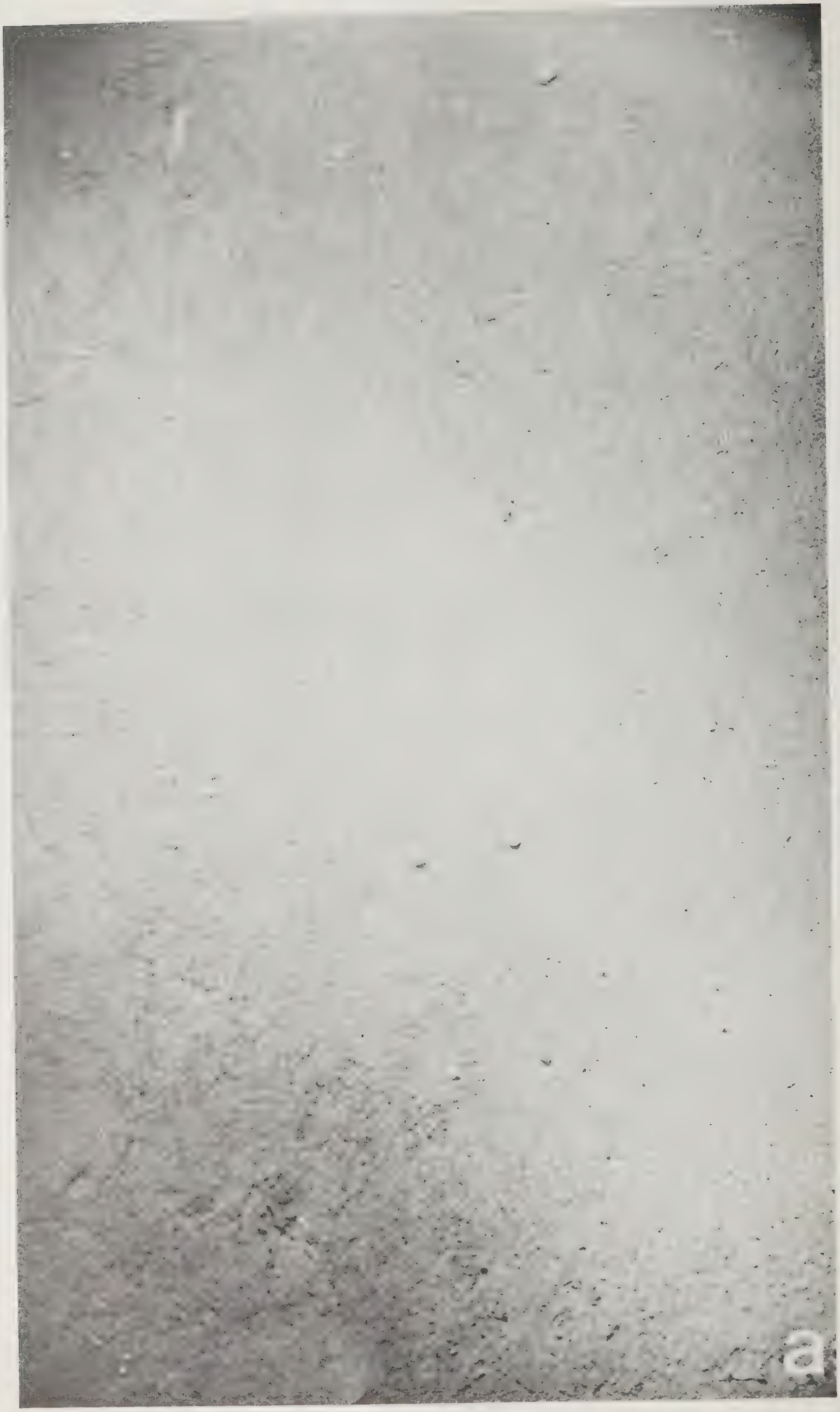


PLATE 1 *a–f*. Representative views of Cartwright sand and gravel unit. Increasing amounts of sand are seen to cover coarse lag from *a* to *f*. *a* and *c*, station 51 (Fig. 3); *b*, *d*, *e*, and *f*, station 59 (Fig. 3). Areas are approximately 2 x 3 m. (Plate 1*a* above)

Plate 1*b*

PLATE 1c

Plate 1*d*

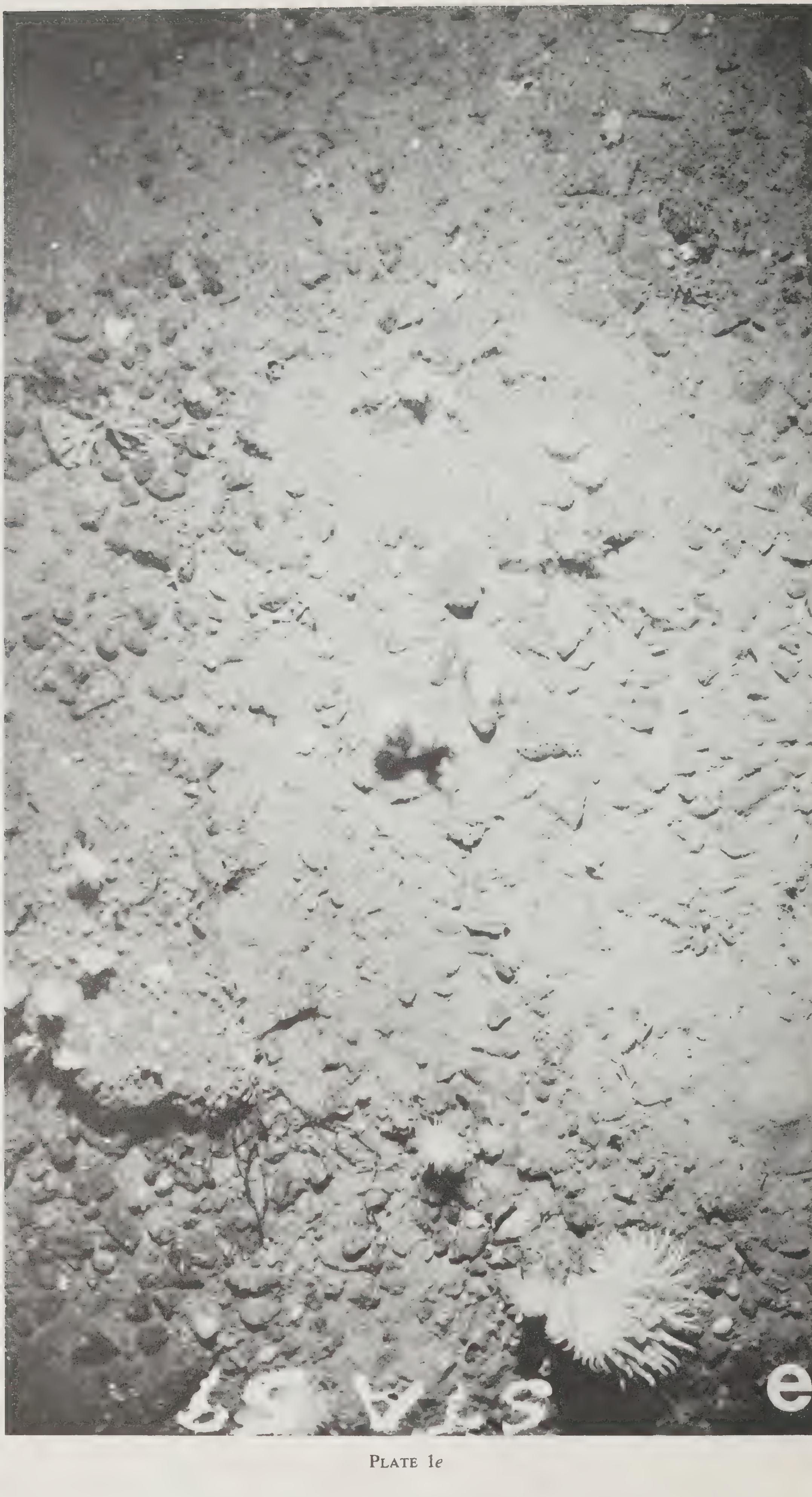


PLATE 1*e*

Plate 1*f*

PLATE 2 *a–f*. Representative views of Groswater unit. Note occurrence of burrows, traces, and accumulation of displaced wormtubes. Ice rafted debris in frames *d* and *f* is encrusted with animal growth. *a*, *b*, *c*, *d*, *e*, and *f* correspond to camera stations 39, 41, 54, 49, 49, and 49 respectively (Fig. 3). Areas are are approximately 2 x 3 m.

PLATE 2*b*

Plate 2c

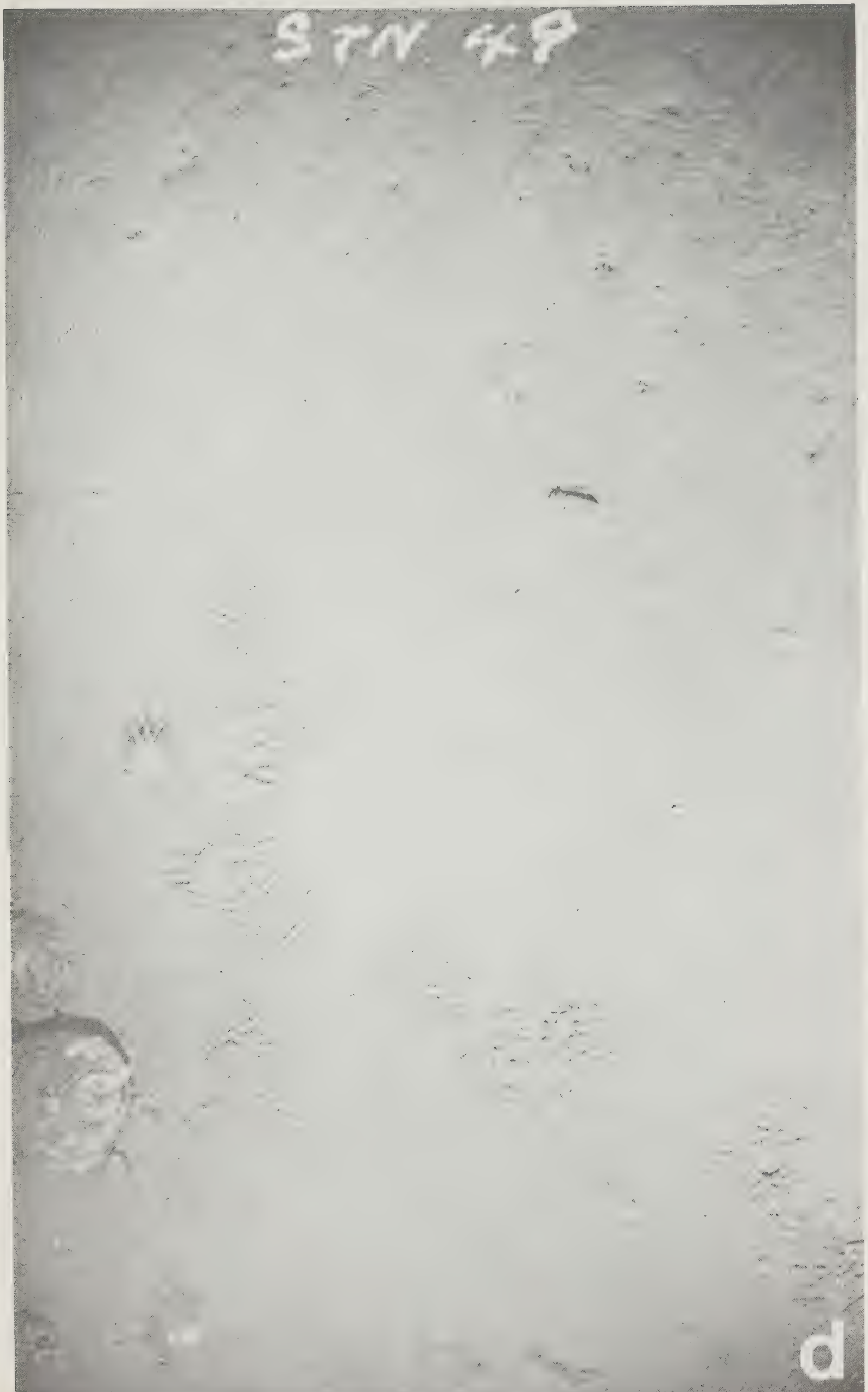


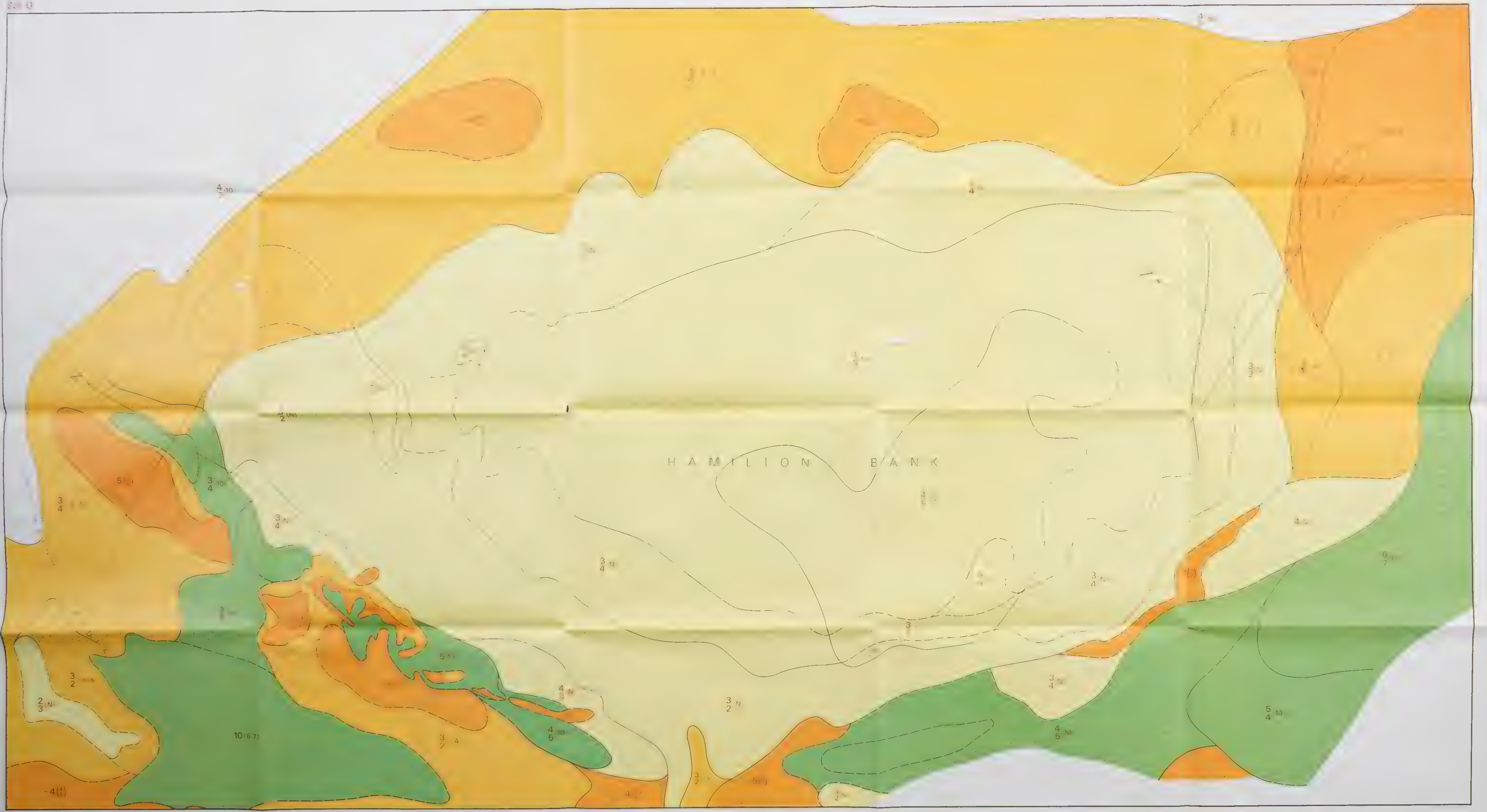
PLATE 2*d*

Plate 2e

Plate 2f

PLATE 3 *a–b*. Representative views of Goose clay unit, camera station 38 (Fig. 3). Areas are approximately 2 x 3 m.

PLATE 3*b*



Labrador Sea | Mer du Labrador

Hamilton Bank | Banc Hamilton

SURFICIAL GEOLOGY | DÉPÔT MEUBLES

Cartographie réalisée par la section de la Cartographie géoscientifique du Service hydrographique du Canada

LEGEND | LÉGENDE

MODAL CLASSIFICATION OF SEDIMENTS | CLASSIFICATION MODALE DES SÉDIMENTS

1976
PUBLISHED BY
THE CANADIAN HYDROGRAPHIC SERVICE
DEPARTMENT OF THE ENVIRONMENT OTTAWA

1976
PUBLIÉE PAR
LE SERVICE HYDROGRAPHIQUE DU CANADA
MINISTERE DE L ENVIRONNEMENT OTTAWA

Labrador Sea
Hamilton Bank

SURFICIAL GEOLOGY

Cartography by the Geoscience Mapping section of the Canadian Hydrographic Service

BATHYMETRIC CONTOURS IN METRES

Transverse Mercator Projection

Scale 1:250 000

This map accompanies Marine Science Paper 14 / Geological Survey of Canada Paper 75-40, "Hamilton Bank, Labrador Margin: origin and evolution of a glaciated shelf", by W.J. van der Linden and R.H. Fillon (Geological Survey of Canada) and David Monahan (Canadian Hydrographic Service).

Mer du Labrador
Banc Hamilton

DÉPÔT MEUBLES

Cartographie réalisée par la section de la Cartographie géoscientifique du Service hydrographique du Canada

COURBES BATHYMÉTRIQUES EN MÈTRES

Projection transverse de Mercator

Échelle 1:250 000

La présente carte se rapporte à l'étude 14 de la Direction des Sciences de la mer et à l'étude 75-40 de la Commission géologique du Canada, intitulée "Hamilton Bank, Labrador Margin: origin and evolution of a glaciated shelf", Elle a été préparée par W.J. van der Linden et R.H. Fillon (Commission géologique du Canada) ainsi par David Monahan (Service hydrographique du Canada).

Labrador Sea | Mer du Labrador

Hamilton Bank | Banc Hamilton

MORPHOLOGY | MORPHOLOGIE

Cartographie réalisée par la section de la Cartographie géoscientifique du Service hydrographique du Canada

COURBES BATHYMETRIQUES EN METRES

Transverse Mercator Projection | Projection transverse de Mercator

LEGEND | LEGENDE

BOTTOM CATEGORIES | CATEGORIES DU FOND

I

IV — Moraine de fond ou topographie de "kame and kettle" couverte

V

INDIVIDUAL FEATURES | TRAITS INDIVIDUELS

large kame | grosse kame

moraine trend (established) | direction du moraine établie

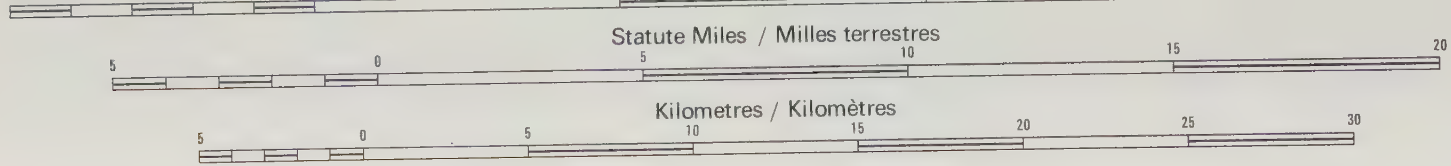
moraine trend (inferred) | direction du moraine déduite

PUBLISHED BY | PUBLIÉE PAR

THE CANADIAN HYDROGRAPHIC SERVICE | LE SERVICE HYDROGRAPHIQUE DU CANADA

DEPARTMENT OF THE ENVIRONMENT, OTTAWA | MINISTERE DE L'ENVIRONNEMENT, OTTAWA

MORPHOLOGY 831-M MORPHOLOGIE



LEGEND / LÉGENDE

BOTTOM CATEGORIES / CATÉGORIES DU FOND

BOTTOM CATEGORIES		CATÉGORIES DU FOND
Irregular, subaqueous kame and kettle topography.	I	Topographie irrégulière de "kame and kettle", sous-marine.
Smooth, acoustically reflective subaqueous outwash plain.	II	Plaine de lavage, lisse. Réflectivité sismique très forte.
Ground moraine, moderately irregular.	III	Moraine de fond; légèrement irrégulière.
Ground moraine or subaqueous kames and kettles mantled with postglacial sediments; moderately irregular.	IV	Moraine de fond ou topographie de "kame and kettle" couverte par des dépôts post-glaciaire; légèrement irrégulière.
Postglacial cover. Smooth acoustically transparent ponded sediments.	V	Couverture post-glaciaire. Dépôts piégés, lisses. Réflectivité sismique très faible.
(Mottled on side-scan sonograms)		(Les sonogrammes de balayage latéral sont tâchetés.)

Labrador Sea / Mer du Labrador

Hamilton Bank / Banc Hamilton

BATHYMETRY / BATHYMÉTRIE

Cartography by the Geoscience Mapping section of the Canadian Hydrographic Service

Cartographie réalisée par la section de la Cartographie géoscientifique du Service hydrographique du Canada

BATHYMETRIC CONTOURS IN METRES

COURBES BATHYMÉTRIQUES EN MÈTRES

Transverse Mercator Projection

Projection transverse de Mercator

Scale 1:250 000

Échelle 1:250 000

This map is based on the Natural Resource Series of maps as indexed below. Information concerning data sources is included on those maps.

La carte classée ci-dessous est basée sur la série de cartes des Ressources Naturelles. Ces dernières fournissent des renseignements sur les sources de données.

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Nautical Miles / Milles marins

Statute Miles / Milles terrestres

Kilometres / Kilomètres

1975
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1975
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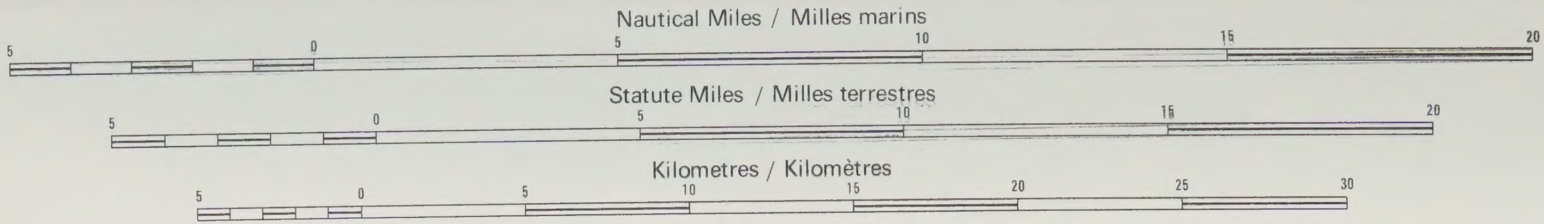
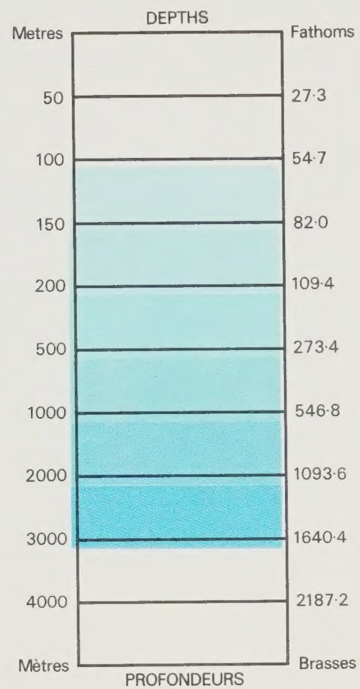
MINISTÈRE DE L'ENVIRONNEMENT, OTTAWA

BATHYMETRY 831-A BATHYMÉTRIE


Nautical Miles / Milles marins
5 0 5 10 15 20
Statute Miles / Milles terrestres
5 0 5 10 15 20
Kilometres / Kilomètres
5 0 5 10 15 20 25 30


DEPTHS
Metres
Fathoms
50
27·3
100
54·7
150
82·0
200
109·4
500
273·4
1000
546·8
2000
1093·6
3000
1640·4
4000
2187·2
Mètres
Brasses
PROFONDEURS